REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*

2. REPORT TYPE
Technical Papers

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

5d. PROJECT NUMBER
2303

5e. TASK NUMBER
M2C8

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Air Force Research Laboratory (AFMC)
AFRL/PRS
5 Pollux Drive
Edwards AFB CA 93524-7048

8. PERFORMING ORGANIZATION REPORT

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Air Force Research Laboratory (AFMC)
AFRL/PRS
5 Pollux Drive
Edwards AFB CA 93524-7048

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release; distribution unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

1121 044

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:

a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
Unclassified	Unclassified	Unclassified	A		Leilani Richardson
					19b. TELEPHONE NUMBER *(include area code)* (661) 275-5015

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. 239.18

62 separate items are enclosed

TP-1998-136

2303 M2C8

MEMORANDUM FOR IN-HOUSE PUBLICATIONS

FROM: PROI (TI) (STINFO) 6 Jul 98

SUBJECT: Authorization for Release of Technical Information, Control Number: AFRL-PR-ED-TP-1998-136
F.B. Mead, L.N. Myrabo and D.G. Messitt (Rensselaer Polytechnic Institute)
"Ground and Flight Tests of a Laser Propelled Vehicle"
AIAA **(Statement A)**

AIAA 98–3735
Ground and Flight Tests of a Laser Propelled Vehicle

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**34th AIAA/ASME/SAE/ASEE
Joint Propulsion Conference & Exhibit
July 13–15, 1998/Cleveland, OH**

AIAA-98-3735

GROUND AND FLIGHT TESTS OF A LASER PROPELLED VEHICLE

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Abstract

A laser propelled Lightcraft vehicle has been successfully flown in a series of experiments conducted at the High Energy Laser Systems Test Facility (HELSTF), White Sands Missile Range (WSMR), NM. The flight tests, conducted under a joint USAF/NASA flight demonstration program, used a single optimized geometry scaled over a range of sizes designed to fly on the 10 kW Pulsed Laser Vulnerability Test System (PLVTS) pulsed carbon dioxide laser. The axisymmetric Lightcraft vehicles were propelled by airbreathing, pulsed-detonation engines with an infinite fuel specific impulse. Schlieren and shadowgraph pictures were taken as a function of time, and laser beam propagation studies were conducted with different focal length telescopes. Spin-stabilized free-flight launches outside the laboratory have been accomplished to altitudes approaching 30 m (100 ft).

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Introduction

In the USA, laser propulsion was first promoted by Kantrowitz.[1] His early analyses dealt with laser heated rockets, ~~and assumed~~ a specific impulse of 1,000 s. The analyses indicated that gigawatt lasers were required to launch sizeable vehicles (1 ton to orbit) at an average acceleration of 10 g's. A principal advantage of the laser propulsion launch system was the capability to rapidly launch many relatively small payloads. Such a system could launch observation or communications relay microsatellites to quickly respond to new requirements or to temporarily replace critical, malfunctioning systems.

Background

The Lightcraft Technology Demonstrator (LTD)[2] is a laser propelled trans-atmospheric vehicle concept developed by Prof. Leik Myrabo at Rensselaer

Polytechnic Institute (RPI) for Lawrence Livermore National Laboratory and the SDIO Laser Propulsion program in the late 1980's.[3] This new launch system was envisioned to employ a 100 MW-class ground-based laser to transmit power directly to the Lightcraft in flight. An advanced combined-cycle engine would propel a 120 kg (265 lb) dry mass, 1.4 m (4.59 ft) diameter LTD, with a mass fraction of 0.5, to orbit. The LTD vehicle would then become an autonomous sensor satellite capable of delivering precise, high quality information typical of today's large orbital platforms.[2]

The dominant motivation behind this study was to provide an example of how laser propulsion could reduce, by an order-of-magnitude or more, the production and launch costs of sensor satellites. The study concluded that a vehicle production cost of \$1,000/kg was realizable, and that launch costs must be limited to less than \$100/kg for laser propulsion to play a significant role in the future of space transportation. Today, our expectations for the use of laser propulsion technology are slightly less ambitious. We envision the launching of 1 kg (2.2 lb) into a low earth orbit (LEO) for less than \$500 of electrical power using a 1 MW CO_2 pulsed electric laser. Production costs of \$3,125 for the 1 kg spacecraft appear reasonable at present.

The LTD concept, as illustrated in Fig. 1, was, and is today a microsatellite in which the laser propulsion engine and satellite hardware are intimately shared.[2] The forebody aeroshell acts as an external compression surface (i.e., the airbreathing engine inlet). The afterbody has a dual function as a primary receptive optic (parabolic mirror) for the laser beam and as an external expansion surface (plug nozzle)

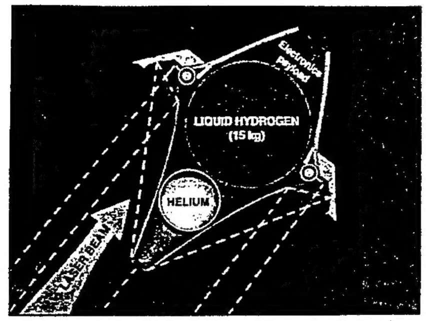

Fig. 1 Schematic of Lightcraft engine.

during the laser rocket mode which is used only in space. The primary thrust structure is the annular shroud. The shroud serves as both inlet and impulsive thrust surface during the airbreathing mode. In the rocket mode, the annular inlet is closed, and the afterbody and shroud combine to form the rocket thrust chamber. The three primary structures (forebody, shroud, and afterbody) are interconnected by a perimeter support frame to which all internal subsystems are attached. Once in orbit, the single-stage-to-orbit (SSTO) LTD vehicle becomes an autonomous sensor satellite capable of delivering precise, high quality information typical of today's large orbital platforms.[2]

Laser Heated Rocket Investigations

Most previous experimental and analytical research into laser propelled vehicles has been concerned almost exclusively with laser heated rockets. The basic principle of a laser heated rocket is to use a remote, high energy laser to heat a gaseous or solid material to a very high temperature, a plasma. In the early years, researchers at Physical Sciences, Inc. (PSI)[4] conducted experiments with gaseous fluids in the type of configuration shown in Fig. 2. Here, the gas (argon or hydrogren) was

injected through the forward wall of the parabolic nozzle where it was rapidly heated to a plasma by a pulsed CO_2 laser. The heated gas was then expanded out the nozzle. Specific impulse values ~~obtained~~ experimentally with hydrogen indicated

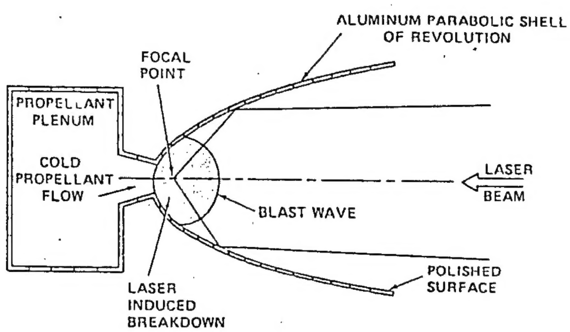

Fig. 2 Schematic of repetitively pulsed laser-powered thruster.

values approaching 3,000 s were ~~achievable~~. Later, gaseous experiments ~~with laser~~ sustained plasmas (LSP)[5] were ~~conducted~~ using the configuration shown in Fig. 3.

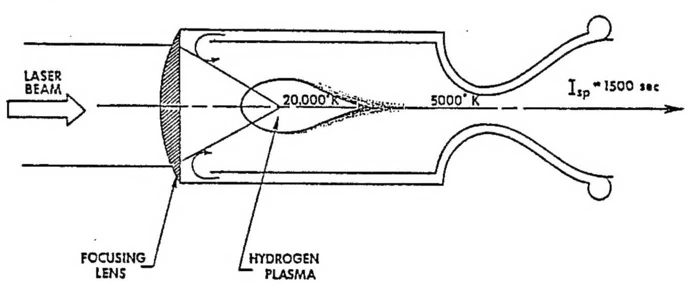

Fig. 3 Schematic configuration for a laser absorption chamber.

This concept uses a CW laser to maintain a hot gaseous core in the center of a fluid flow field. The hot core then transfers heat to the surrounding gas. The core can be maintained at very high temperatures because the walls are shielded and cooled by the outer gaseous flow.

An experimental investigation of a solid propellant laser heated rocked, reported in Ref. 6, was performed with a single pulse ~~of a 60 J~~ CO_2 laser. The laser ~~pulse width~~ was ~~100~~ µs, and was focused ~~onto the solid propellant~~ by a parabolic ~~mirror which also~~ served as the engine's nozzle ~~similiar to that~~ illustrated in Fig. 2. In ~~this concept, the solid~~ material was ablated, ~~vaporized, and rapidly~~ heated to a plasma. ~~The impulse obtained by~~ the the heating and expansion ~~of the~~ solid propellant was ~~measured using~~ a ~~ballistic~~ pendulum. Specific impulses ~~up to 500~~ s were obtained with ~~graphite. Coupling~~ coefficients, the ratio of measured impulse to energy delivered to the engine by the laser, were ~~reported~~ to be between 20 and 920 N-~~s/MJ~~, ~~depending~~ on the type of solid propellent tested. Coupling coefficients for ~~laser breakdown~~ of ~~ambient air~~ were ~~reported~~ in ~~the~~ range ~~of 60~~ to ~~300~~ N-s/MJ. ~~These~~ results were observbed ~~to~~ ~~depend~~ on ~~the laser beam~~ flux being delivered to ~~the~~ polished aluminum primary ~~optic. this~~ dependence of the coupling on the incident beam area was attributed to oxidel ~~formation~~ on the optic and low optical ~~quality of the~~ parabolic mirror.

A second experiment, with a 11 J, 3 µs, CO_2 laser powering a conical nozzle, helium fueled rocket obtained a specific impulse of 900 s and a coupling coefficient of 170 N-s/MJ over two laser pulses.[7] Supporting analyses of laser propelled rockets[8] indicated that a megajoule laser operating at 350 pulses per second (350 MW average power) could accelerate a one ton rocket at 10 g's in a vacuum.

Airbreathing Laser Propulsion Experiments

An airbreathing laser propulsion system has the advantage that no fuel or

propellant is carried onboard. As in all laser propulsion concepts, the energy or power is provided by a ground based, high energy laser, focused by onboard optics to heat air flowing into the engine thrust chamber. Pulsed detonation wave laser engines using atmospheric air as the propellant have an infinite specific impulse. And because this concept does not need to carry onboard fuel, the vehicles can be "very" lightweight. The Lightcraft concept is a specific example of an airbreathing laser propulsion system. But, airbreathing can only be used within the atmosphere, and vehicles going into space must in reality carry some propellant onboard for operation in the vacuum of space. Being able to operate with air or an onboard propellant is a "dual-mode" operating capability. In the case of the Lightcraft, propellant must be carried onboard for use above an altitude of 30 km (18.6 mi) or roughly 100,000 ft. Thus, for an actual space mission, the Lightcraft would carry about half its weight in propellant. This has an added advantage in that while the Lightcraft must pay a weight penalty to operate in space, a small amount of propellant may be used for active cooling during the boost phase of the mission through the atmosphere.

Agreev, et. al.[9] presented computed and experimental results for an air breathing, laser propelled engine. The experiments were conducted with a low energy (5 J/pulse), pulsed CO_2 laser to determine the optimum nozzle angle and length. The experimental configuration was similar to the laser rocket depicted in Fig. 3, with a parabolic nozzle but ambient air as the working fluid. Peak coupling coefficients of up to 500 N-s/MJ were reported for these static tests. Computations with an inflow of air from a simulated inlet resulted in higher performance.

Some meaningful simulation experiments were conducted with a full scale (1 m diameter focal length) Lightcraft optical segment focused on a flat plate. The high energy, pulsed 1 µm PHAROS III neodymium-glass laser at the Naval Research Laboratory (NRL) was used to investigate the impulse imparted to this flat plate by laser induced air breakdown.[10] The impulse was measured using a velocity meter coil and a pendulum suspended from the test cell ceiling. The test cell was at atmospheric pressure. Single laser pulses varying from 48 to 350 joules were brought to a line focus at the target surface by a spherical lens. The pulse width varied from 5 to 30 ns. Coupling coefficients of 75 to 132 N-s/MJ were obtained on steel and aluminum flat plates. The coupling coefficient increased to a maximum of 178 N-s/MJ when a 0.5 T magnet was inserted at the target surface.

None of these previous experimental investigations of laser propelled rockets or air breathing engines obtained actual flight test data. The objective of the current Lightcraft Technology Demonstration (LTD) program is to conduct, before the end of the calendar year 1998, a flight of a specially designed, ultralight Lightcraft to an altitude of about 100 m (328 ft) using the PLVTS laser located at the HELSTF, WSMR, New Mexico. Initial free flight launches at the HELSTF began with indoor experiments conducted over the days of 21-24 April 1997. Outdoor free flight launches began during the days of 3-5 November 1997, and have continued to the present.

Experimental Apparatus

Several variations on the basic Lightcraft design were examined during the course of the test program.[11] The current

baseline Model 200 Series vehicle has a nominal 14-cm (5.5 in) focal length diameter, weighs 40-gm (1.4 oz), and is designed to fly on the 10 kilowatt average power level available from the PLVTS pulsed carbon dioxide laser (350 J pulses at 30 Hz, 18 μs pulse duration). The Model 200 Series has been fabricated in a variety of sizes (See Fig. 4) varying from eleven-tenths to two-thirds the nominal size with a corresponding weight range of 52 gm (1.8 oz) to 19 gm (0.7 oz).

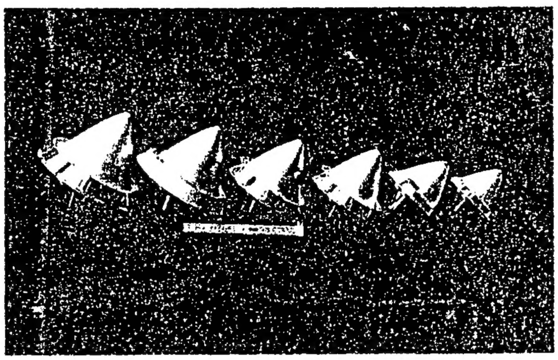

Fig. 4 Model 200 series Lightcraft

All of these variations have been flown. Each of the axisymmetric vehicles was propelled by an airbreathing pulsed detonation engine (PDE) with an infinite fuel specific impulse.

Lightcraft Engine

As described above, the Lightcraft engine consists of a parabolic base which serves as a plug nozzle and also as the main optic, cf. Figs 1 and 3. The vehicle is axisymmetric, with an annular shroud which encompasses the focus of the parabolic optic. Each Lightcraft vehicle shape is machined from solid 6061-T6 aluminum blocks using a CNC lathe, and the assembled vehicles are statically balanced around the longitudinal axis prior to flight.

For horizontal flight tests ~~and the~~ initial vertical flight tests in the ~~laboratory~~, the Lightcraft was positioned on a thin steel wire.[11] Steel roller bearings ~~and nylon~~ sliding ~~bearings~~ were used to reduce ~~friction~~ between ~~the~~ vehicle and the ~~wire. Steel~~ ~~sliding~~ bearings are also used ~~on the vertical~~ "free flight" experiments to facilitate rapid separation from the short launch support rod.

PLVTS Laser

The PLVTS laser was used to remotely provide the laser energy for the laboratory experiments, horizontal wire flight tests, and vertical wire guided and free flight tests. PLVTS is a closed cycle CO_2 laser loc~~ated at the~~ HELSTF at WSMR, New Mexico. The PLVTS laser is an AVCO-built HPPL-300 laser.[12] PLVTS ~~has been~~ upgraded to deliver pulsed laser energy to the Lightcraft vehicle at levels up to 350 J/pulse at a pulse repetition rate of 30 Hz, with a pulse width of 18 μs. This upgrade was accomplished in February 1998. The beam is always delivered to the target by turning flats. An actuated mirror was used for active pointing and tracking of the laser beam in horizontal wire-guided flights and some of the initial laboratory vertical flights.

The PLVTS laser produces a 10 cm (3.94 in) square laser beam profile directly out of the laser cavity.[11] Beam propagation effects have been studied by varying the beam size in the near field and observing the energy distribution in the far (diffraction limited) field. Smaller near field beams are typically used on the smaller, lighter weight models.

The average pulse energy was measured during each thrust stand experiment, and following each flight test

series.[11] A VXI mainframe with a Tektronix VX4244 16 channel digitizer and a VX4780 16 channel differential amplifier was employed to acquire Lightcraft performance data. The VXI was controlled by a laptop computer using repetitive pulses from the PLVTS laser.[11]

Results and Discussion

Review

Initial laser propulsion experiments focused on measurement of thrust and short, wire guided horizontal flights in order to prove the Lightcraft concept. Lightcraft engine models were suspended from a pendulum and the induced current in an attached coil was used to determine the imparted impulse from a single laser pulse.[10]

A piezoelectric force sensor was mounted to Lightcraft models and fixed to a thrust stand to determine the impulse imparted to the engine by the high energy laser. Initial results from the thrust stand were compared with the previous pendulum measurements.[11] The engine performance was found to scale linearly with pulse energy, at average energies from 300 to 850 J.[11]

Recent Results

The green (0.532 μm) doubled output from a YAG laser was used for Schlieren and shadowgraph studies of the flow field at the rear of the Lightcraft engine during the pulsed detonation wave expansion. The configuration used for Schlieren tests is illustrated in Fig. 5. For the shadowgraph pictures, the lens and knife edge on the

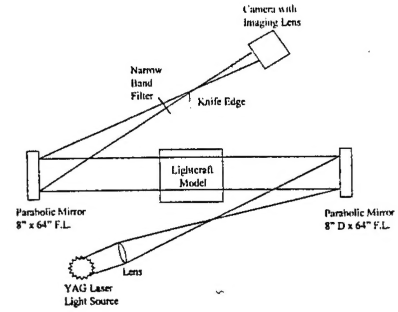

Fig. 5 Laser Propulsion Schlieren Apparatus

camera side of the experiment were removed. A narrow band filter was used to remove broadband radiation from the plasma. The laser had to be severely attenuated from the 200 mJ/pulse to avoid over exposing the film in the camera. The YAG laser had a pulse duration of 3 ns with a timing jitter in the sub-nanosecond range. The PLVTS laser had a pulse duration of 18 μs. The YAG laser was triggered by the PLVTS firing circuit with a built-in controllable delay. The delay in the circuit allowed pictures to be taken at time increments varying from zero to 6,000 μs in relationship to the detonation at the focal point of the engine. Figs. 6 and 7 illustrate the flow field at two different times with pictures taken with the shadowgraph apparatus. The progression of the shock

Fig. 6 Shadowgraph Picture at t=40 μs.

recent outdoor flights which started in November 1997.

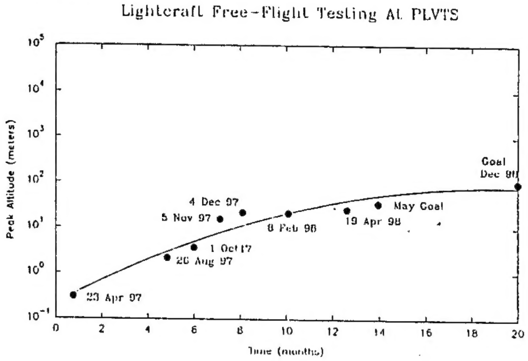

Fig. 10 Test flight altitudes with PLVTS laser at HELSTF/WSMR.

As can be seen in Fig 10, the goal is quite challenging but probably realistic in terms of time and developments of the Lightcraft concept. The biggest problem in attaining the altitude goal is the poor beam quality of the PLVTS laser. This means that significant power losses occur at the vehicle due to beam spread, and thus a large reduction in thrust.

Conclusions and Future Work

A laser propelled Lightcraft vehicle has been successfully flown in a series of experiments conducted at the HELSTF, WSMR, NM. The flight tests, conducted under a joint USAF/NASA flight demonstration program, used a Model 200 series class of vehicles ranging in weight from 19 to 52 gm (0.8 oz to 1.8 oz). These vehicles were designed to fly on the 10 kW average power PLVTS pulsed carbon dioxide laser. The axisymmetric Lightcraft vehicles were propelled by airbreathing, pulsed-detonation engines with an infinite fuel specific impulse. Impulse coupling coefficients were calculated from ballistic pendulum as well as a piezoelectric load cell tests and fell in the range of 100 to 143 N-s/MJ. Horizontal wire-guided flights up to 121.3 m (398 ft), using a laser beam pointing and tracking guidance system, have demonstrated up to 2.3 g's acceleration measured by a photo optic array. Schlieren, shadowgraph, and beam propagation (to 90 m) studies have been accomplished. And, spin-stabilized vertical free-flights have been accomplished outdoors to altitudes approaching 30 m.

Acknowledgements

The authors would like to thank the members of the U.S. Army's PLVTS laser engineering team (Mr. Stephen Squires, Mr. Chris Beairsto, and Mr. Mike Thurston) for providing the beam power for these experiments, and Mr. James Shryne of Rohmann Services, Inc., for his excellent photography of the Lightcraft experiments and flight tests. Finally, we want to acknowledge the Air Force Research Laboratory and NASA's Marshall Space Flight Center for co-sponsoring this Lightcraft technology demonstration program.

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